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April 30, 1993



Dr. Robert Petre
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Laboratory for High Energy Astrophysics
NASA Goddard Space Flight Center
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Dear Rob:

Please find enclosed progress reports for my NASA funded research programs involving ROSAT pointed observations. Since we have now received data and funding for AO-1, AO-2, and AO-3, I have decided to organize this report according to the scientific programs rather than by AO number. Much of the funded research represents a continuation of effort between the various AOs.

If you have any questions about this report, I will be happy to answer them via phone or via E-mail at jburns@nmsu.edu.

Sincerely yours,

A handwritten signature in cursive script, reading 'Jack O. Burns'.

Jack O. Burns
Department Head & Professor

(NASA-CR-193784) ROSAT
OBSERVATIONS OF CLUSTERS WITH
WIDE-ANGLE TAILED RADIO SOURCES
Progress Report (New Mexico State
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ROSAT OBSERVATIONS OF CLUSTERS WITH WIDE-ANGLE TAILED RADIO SOURCES

NASA Grant numbers: NAG 5-1737, Aug. 15, 1991 - Aug. 15, 1993.
NAG 5-1819, Nov. 1, 1991 - Oct. 31, 1993.

Principal Investigator: Jack O. Burns, New Mexico State University

The goal of these ROSAT PSPC pointed observations was to understand the nature of X-ray emission associated clusters that contain luminous wide-angle tailed (WAT) radio sources identified with the centrally dominant cluster galaxies. These 500 kpc diameter radio sources are strongly affected by confinement and interaction with the intracluster medium. So, a complete picture of the origin and evolution of these radio sources is not possible without detailed X-ray observations which sample the distribution and temperature of the surrounding hot gas.

Two WAT clusters have been observed with the ROSAT PSPC to date. The first is Abell 2634 which contains the WAT 3C 465 and was approved for observations in AO-1. Unfortunately, these observations were broken into two widely separated pieces in time. The first data set containing about 9000 sec of integration arrived in mid-March, 1992. The second data set containing about 10,500 sec arrived just recently in early April (after a first tape was destroyed in the mail). The second cluster is 1919+479 which was approved for observations in AO-2. These ROSAT data arrived in October 1992.

We are currently awaiting new PROS software which will allow us to merge the QP files from the 2 databases on A2634. In spite of this delay, we have made some progress and have some initial conclusions on these clusters. First, images of the ROSAT emission for these two clusters is shown overlaid onto grey-scale VLA radio maps. There are prominent extensions of X-ray emission between the radio tails in both clusters. Interestingly, these X-ray extensions do not follow the optical light emission from the cD galaxies which is generally more symmetrical. We are working on an interpretation that involves a recent merger of these clusters with a smaller galaxy group. Such extensions of X-ray emission are post-merger signatures which appear in our new hybrid hydro/N-body simulations (Roettiger, Burns, & Loken, 1993, ApJ Lett., in press). We see similar X-ray extensions in lower resolution Einstein images of other WAT clusters as well as in images from the ROSAT all-sky survey which have considerably poorer S/N.

Second, we have performed a preliminary comparison of the distribution of optical galaxies in both A2634 and 1919+479. There is generally good agreement between the positions of X-ray clumps and subgroups of galaxies within the clusters. With these new data, we will be able to perform a detailed investigation of subclustering which again can test our merger model.

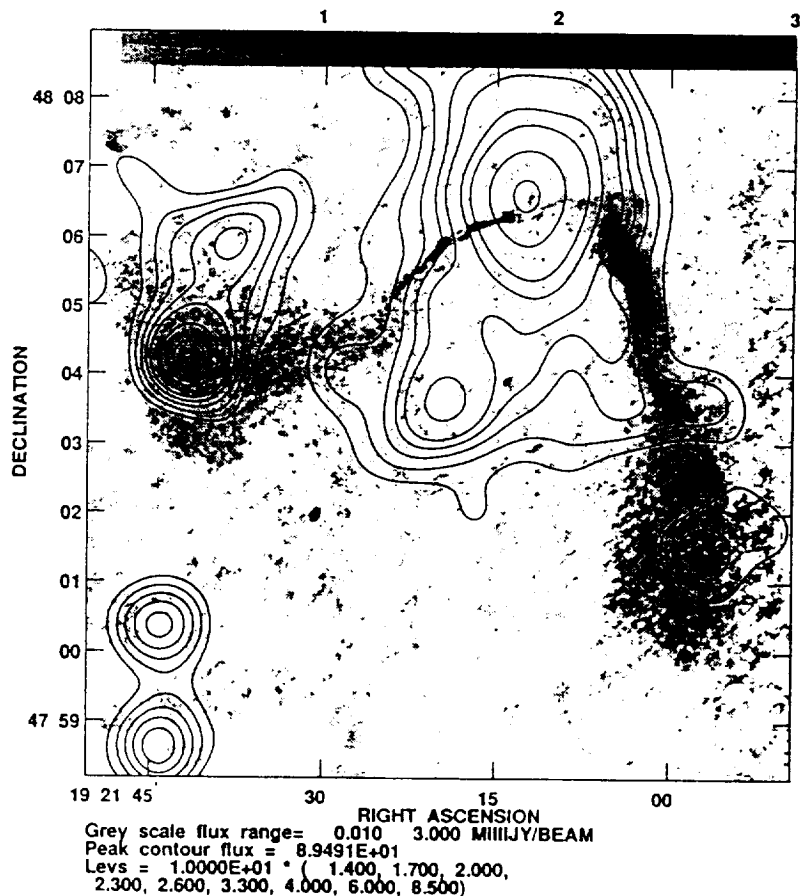
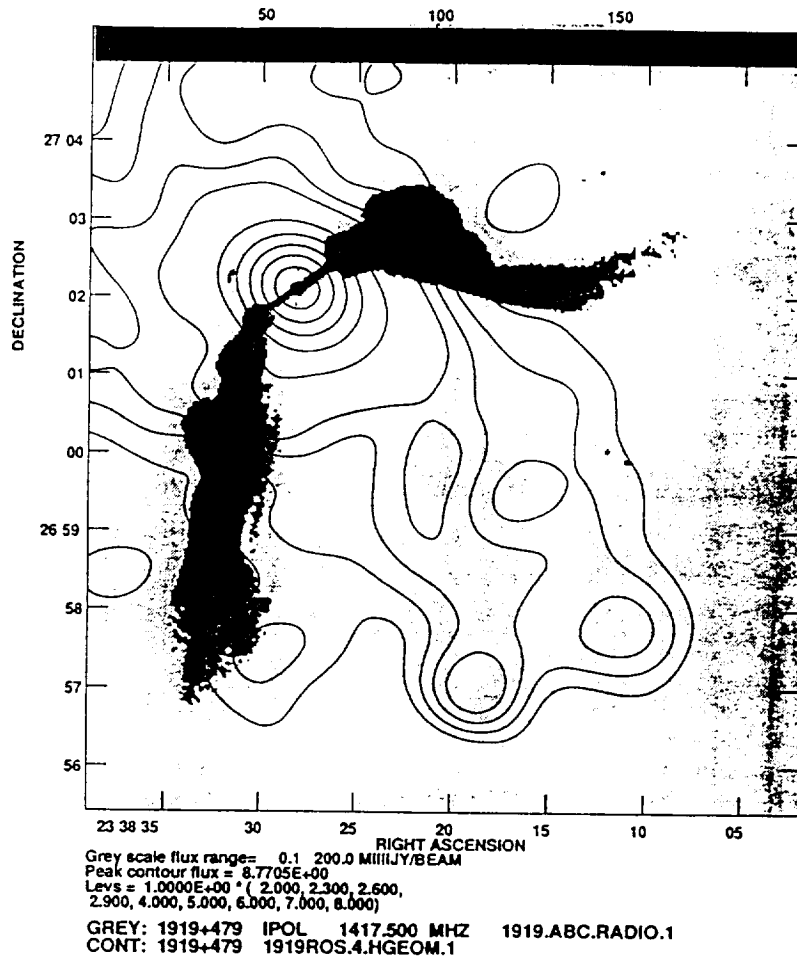
Third, we have begun to examine the temperature distribution in both clusters using the limited ROSAT spectral information. The

average temperatures are about 3 keV. However, there is some evidence of a slightly cooler component at the very core of the clusters. It is not yet clear how significant any temperature gradient is in these clusters although it appears to be much less than in typical cooling flow clusters such as Abell 85.

These preliminary results have now been presented at several conferences and will appear in conference proceedings. These include:

1. "Radio Galaxies, X-Ray Subclumps, and Mergers Within Clusters of Galaxies", 1993, J. Burns, G. Rhee, K. Roettiger, & F. Owen, *Observational Cosmology* (Proceedings of Sep. 1992 conference in Milan), eds. G. Chincarini, A. Iovino, T. Maccacaro, & D. Maccagni (ASP Conference Series, San Francisco), in press.
2. "The Dynamics of Galaxy Clusters Containing Wide-Angle Tailed Radio Sources", 1993, J. Pinkney, J. Burns, G. Rhee, J. Hill, *BAAS*, 24, 1193.

A copy of paper 1 above is enclosed.



ROSAT and VLA images of two galaxy clusters with Wide-Angle Tailed (WAT) radio galaxies. The contours are ROSAT PSPC X-ray surface brightness smoothed with a 1' Gaussian. The grey-scales are VLA radio images at 6-cm (top for 3C 465) and 20-cm (bottom for 1919+479).

ROSAT OBSERVATIONS OF POOR GALAXY CLUSTERS WITH EXTENDED RADIO SOURCES

NASA Grant Numbers: NAG 5-1737, Aug. 15, 1991 - Aug. 15, 1993
NAG 5-1819, Nov. 1, 1991 - Oct. 31, 1993

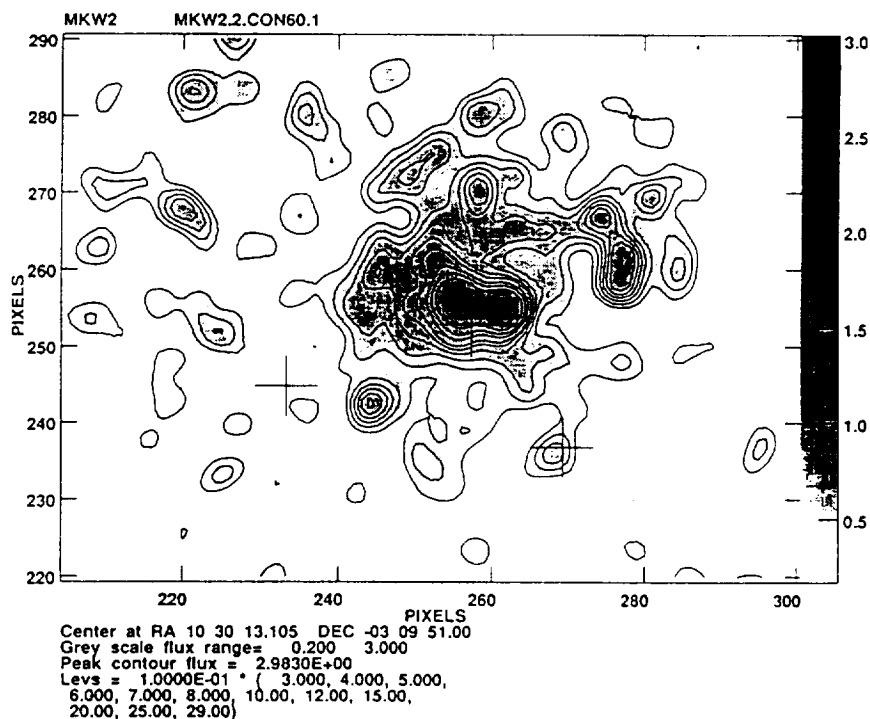
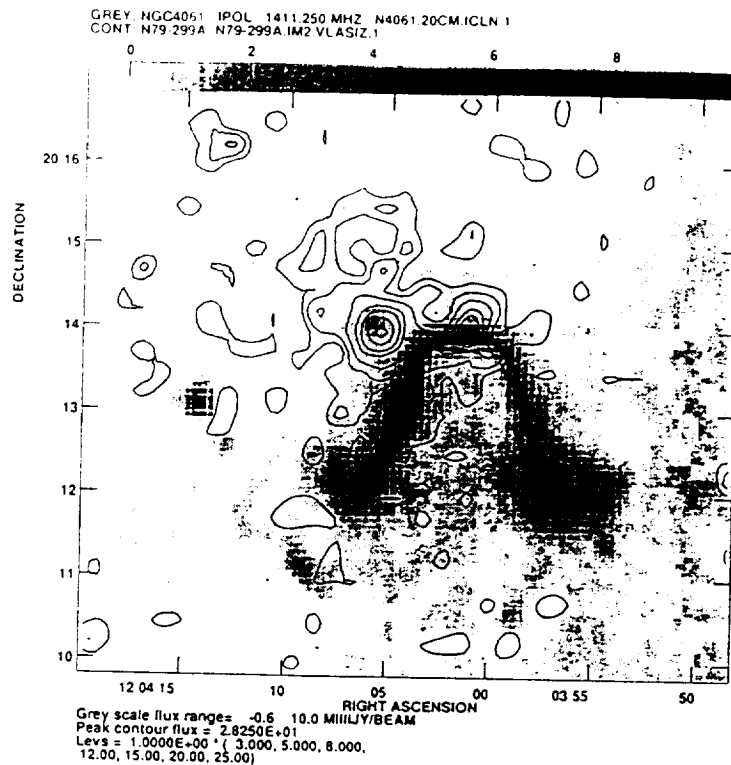
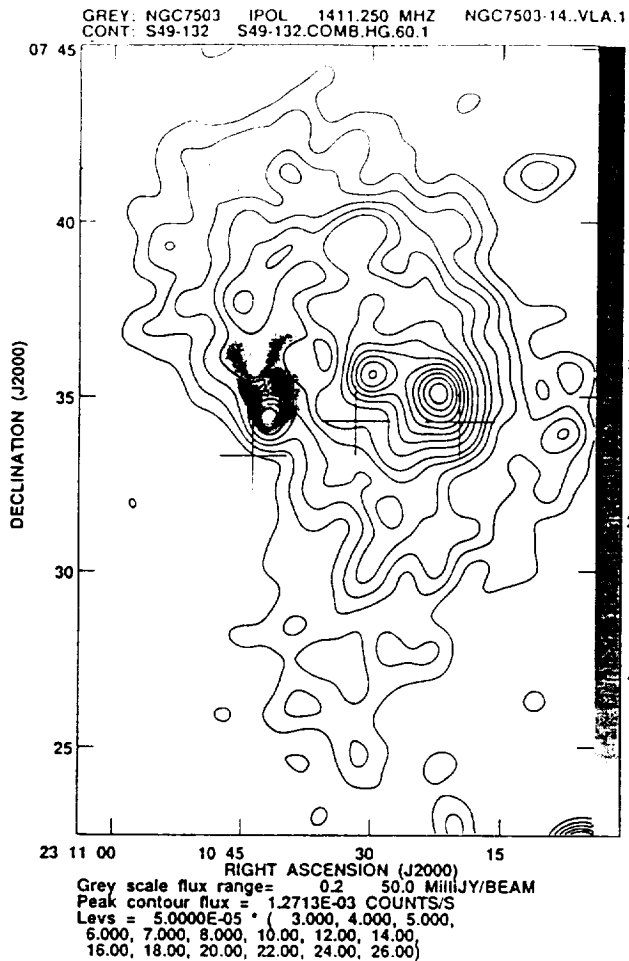
Principal Investigator: Jack O. Burns, New Mexico State University

The goal of these ROSAT PSPC observations is to understand X-ray emission in poor groups. This is an important issue since most galaxies reside in poor clusters rather than the rich clusters which are much better studied. These particular clusters were selected for ROSAT observations because they contain extended, tailed radio sources which must be strongly interacting with the intracluster medium. These radio sources are good predictors of the X-ray luminosity of poor clusters since the hot ICM confines the extended radio plasma.

Three poor groups have been observed to date by ROSAT for this project. The enclosed figures show overlays of the cluster X-ray emission (contours) onto grey-scale VLA images of the radio emission. In A0-1, N79-299A (NGC 4061) was observed for about 12,000 sec. In A0-3, two additional poor clusters, S49-132 (NGC 7503) and MKW2, were imaged. The data for S49-132 came in two observing sessions with the data tapes received in August 1992 and in March 1993. We are awaiting new PROS software to combine the QP files. The ROSAT data for MKW2 arrived in March 1993.

These three poor clusters reveal an interesting diversity of X-ray structures. S49-132 resembles a scaled-down version of a rich cluster with extended, diffuse X-ray emission filling the group. The U-shaped head-tail radio source appears to be in the outer portions of the group and is likely produced by motion through the surrounding ICM. However, this cluster is quite poor in the optical with only 3 Zwicky galaxies known to compose the group. On the other hand, MKW2 and N79-299A have more clumpy X-ray emission which appears to be associated with individual galaxies. There is some extended emission but the fraction of the total X-ray luminosity in extended gas not associated with galaxies is smaller in these two clusters than in S49-132. We believe that the radio tailed source in N79-299A is likely produced by the close passage of the radio galaxy near another bright galaxy in the group; the ram pressure resulting from the passage of the radio source through the gaseous halo of the second galaxy appears sufficient to bend the radio tails.

A preliminary report on N79-299A was made at the Observational Cosmology meeting in Milan. A copy of the paper from the proceedings is enclosed.



ROSAT and VLA images of poor clusters of galaxies. The crosses in these images represent the locations of Zwicky galaxies which are the brightest cluster members. The X-ray maps have all been smoothed with a 1' Gaussian beam and the radio maps generally have 5"-10" resolution. In the images of S49-132 and N79-299A at the top, the contours are ROSAT X-ray surface brightness and the grey-scale is the radio emission. In the bottom image of MKW2, contours and grey-scale are both of the X-ray emission.

To appear in *Observational Cosmology*, eds. G. Chincarini, A. Iovino, T. Maccacaro, & D. Maccagni, ASP Conference Series.

RADIO GALAXIES, X-RAY SUBCLUMPS, AND MERGERS WITHIN CLUSTERS OF GALAXIES

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ABSTRACT Einstein and ROSAT x-ray images are used to examine the gaseous environments around a large sample of radio galaxies in rich and poor clusters. The observed clumping of x-ray emission around the radio galaxies suggests that clusters are dynamically evolving at the present epoch and that cluster mergers affect the generation and evolution of galaxy radio emission. Thus, radio galaxies may be good pointers to clusters or cluster regions which are dynamically active.

INTRODUCTION

During the last 12 yrs, two of us (Owen & Burns) have been involved in extensive radio frequency surveys of clusters of galaxies using the VLA at 20-cm. We have imaged hundreds of radio sources identified with galaxies in both rich (Zhao *et al.* 1989; Owen *et al.* 1992) and poor (Burns *et al.* 1987) clusters, in both the northern and southern hemispheres. From our investigations of the statistics of cluster radio galaxy emission, several interesting questions have emerged concerning the nature of the radio sources and their environs. These questions include:

- (1) Why is the shape of the radio luminosity function identical for radio galaxies in and out of rich clusters? One might naively expect, for example, that the higher confining thermal gas pressure within the intracluster medium (ICM) would produce larger magnetic field energy densities and higher radio luminosities for rich cluster sources. But, this is not observed.
- (2) Why does the probability of radio emission from a galaxy not depend upon cluster galaxy density? One might have anticipated more galaxy interactions and thus more radio-loud galaxies as cluster richness increased. But, again, this is not observed.
- (3) Why are tailed radio sources found in both rich and poor clusters? The U-shaped jets in rich cluster head-tail radio sources (*e.g.*, O'Dea & Owen 1985) are believed to be bent by dynamic pressure ($\rho_{ICM} v_g^2$) resulting from transonic motion of the radio galaxy through the ICM (*e.g.*, Jones & Owen 1979). This dynamic pressure is reduced by factors of 10-100 due to smaller gas densities

(Burns *et al.* 1981; Price *et al.* 1991) and lower velocity dispersions in poor versus rich clusters. Yet, spectacular versions of head-tail sources, as in Fig. 1, are found in poor clusters.

(4) Why do cluster-wide radio halos avoid clusters with cooling cores? The rare, Mpc-sized radio halos, typified by Coma (Kim *et al.* 1990), are not associated with clusters that possess x-ray cooling inflows. Only smaller mini-halos with extents of a few hundred kpc (confined to regions near the cooling core) are observed in clusters such as Perseus which contain high mass inflows (Burns *et al.* 1992).

We propose two hypotheses to explain the above observations. First, it is the local rather than the global cluster environment that determines a galaxy's radio properties. Second, cluster/subcluster merging, which is increasingly observed with ROSAT (*e.g.*, Briel *et al.* 1991), influences the production, evolution, and shaping of extended radio galaxy emission. In the following, we present evidence for and consequences of these hypotheses.

EVIDENCE SUPPORTING HYPOTHESES

Einstein/VLA Correlative Study

In Rhee, Burns, & Owen (these proceedings), we present examples of the radio and x-ray morphologies for clusters which have extended 20-cm VLA emission and have Einstein IPC images. We find a strong coincidence between radio galaxy positions and clumps or extensions of x-ray emission. Unfortunately, the Einstein database is not statistically complete, but it is hopefully representative of cluster x-ray morphologies.

ROSAT/VLA Correlative Study

To overcome the limitations of the Einstein database, we have begun a correlative study of VLA cluster radio galaxies and x-ray emission using the ROSAT all-sky survey (Owen, Burns, Voges, & Böhringer 1992). To simplify our initial comparisons, we have examined x-ray emission around a complete sample of cluster radio galaxies with $0.06 \leq z \leq 0.09$. Once again, we find a strong correlation between x-ray clumps and radio galaxies; 76% of the radio sources have x-ray peaks within 5' of the radio positions (54% of these have peaks within 1').

If the clumped x-ray emission is primarily caused by free-free radiation, both the Einstein and ROSAT images appear to support our contention that the local clumping of gas around the radio galaxies may be most influential in determining the radio properties.

Poor Clusters

The above results appear to extend to poor clusters, as well. In Fig. 1, we show a VLA grey-scale image of the head-tail radio source associated with NGC 4061 (Batuski *et al.* 1993) superposed on a ROSAT PSPC image of the poor cluster N79-299A (Burns *et al.* 1993). This cluster contains only 10 Zwicky-cataloged galaxies (Burns *et al.* 1987); two of the brightest galaxies (NGC 4061 & 4065) are associated with two clumps of x-ray emission surrounding the galaxies. The radial velocity difference between the galaxies is 857 km s^{-1} . We believe that the head-tail source may have formed as a result of NGC 4061 interacting with

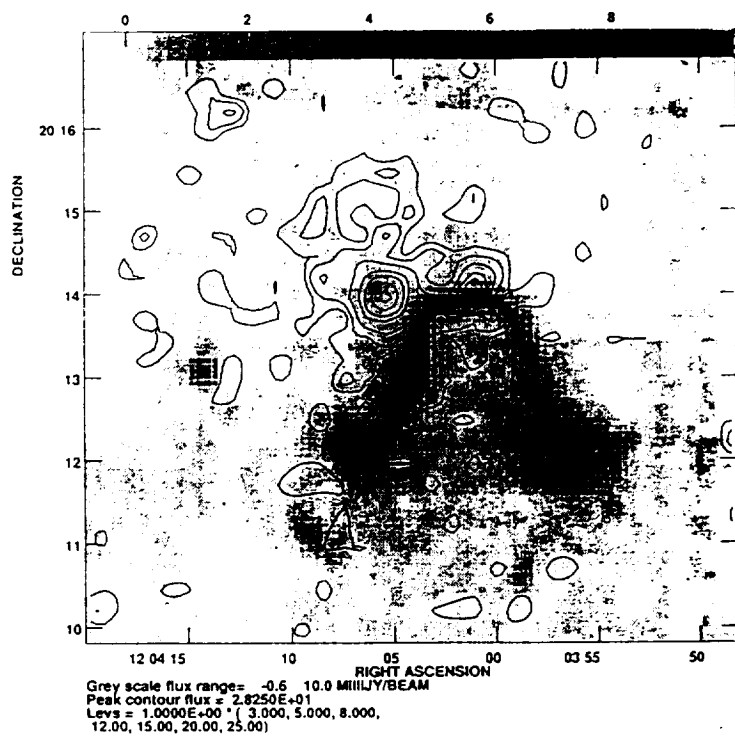


Fig. 1. Overlay of ROSAT x-ray surface brightness contours onto a grey-scale image of the radio emission in the poor cluster N79-299A.

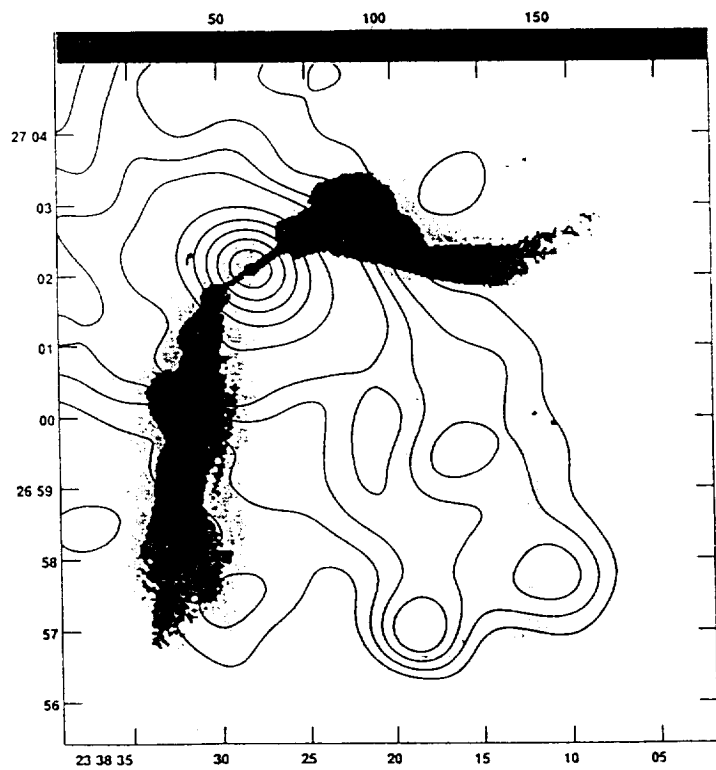


Fig. 2. Overlay of ROSAT x-ray contours onto a grey-scale radio image of Abell 2634/3C 465.

the gaseous halo of NGC 4065 – the relative galaxy velocities and the dense hot gas near the galaxies appear to have produced sufficient local ram pressure to bend the radio jets and form the head-tail source.

Wide-Angle Tailed (WAT) Radio Galaxies

WATs are typically 200 kpc diameter radio sources associated with centrally dominant cluster galaxies. They have straight jets emerging from the galaxy nucleus which disrupt and symmetrically bend forming diffuse tails at distances of ≈ 10 kpc from the core. The prototype is 3C 465 in Abell 2634 shown in Fig. 2.

Three observations suggest an interesting connection between the cluster environment and the radio structure. First, there is a strong correlation between the position angles of the major axes in the radio, x-ray, and optical. In Fig. 2, we see an excess of x-ray emission between the radio tails (similar orientations of the x-ray major axes with respect to the radio tails is seen in other WAT clusters; Rhee *et al.*, these proceedings). The optical major axis is also aligned with the x-ray but is symmetrical with respect to the galaxy nucleus. Second, unlike 70%-90% of clusters with dominant galaxies (Edge *et al.* 1992), WAT clusters generally do not have x-ray cooling cores. Third, although an ≈ 200 km s⁻¹ peculiar motion of the cD is observed in A2634 (Pinkney *et al.* 1992), it is not enough to explain the bending of the tails which requires ≈ 1000 km s⁻¹ motion of the radio plasma relative to the ICM (Eilek *et al.* 1984).

Recently, we performed new, sophisticated hybrid N-body/Eulerian-hydrodynamic numerical simulations of cluster/subcluster mergers which may explain many of the features seen in WAT clusters (Roettiger, Burns, & Loken 1992). For example, in Fig. 3, we see asymmetrical elongations in the ICM gas caused by perturbations in the cluster potential and by shocks. These are signatures of past mergers that may be present in A2634. Furthermore, heating of the central gas via shocks as seen in our simulations probably destroy cooling inflows – another merger signature. Finally, we see post-merger residual ICM gas motions in the simulations which are 1000's of km s⁻¹ – leading to sufficient dynamic pressure to bend the radio tails.

Cluster Radio Halos

Similar merger events may explain the anticorrelation between cluster radio halos and cooling inflows (Burns *et al.* 1992). Recent mergers, as suggested by new ROSAT data on Coma and A2256, have significant amounts of kinetic energy needed to generate extensive cluster-wide microturbulence in the ICM. Such turbulence, then, may amplify primordial seed magnetic fields to μ G strengths (*e.g.*, De Young 1992; Ruzmaikin *et al.* 1989) and accelerate relativistic electrons over large scales (Jaffe 1980), thus creating cluster-wide halos. On the other hand, cooling flows in clusters such as Perseus may suppress the outward advection of cluster *B*-fields and confine mini-halos to the cooling core (Burns *et al.* 1992).

CONCLUSIONS

We suggest from the strong correlation between x-ray subclumps and radio galaxies that the local, rather than the global, gaseous environs around such galaxies most strongly influence the radio properties. In addition, mergers

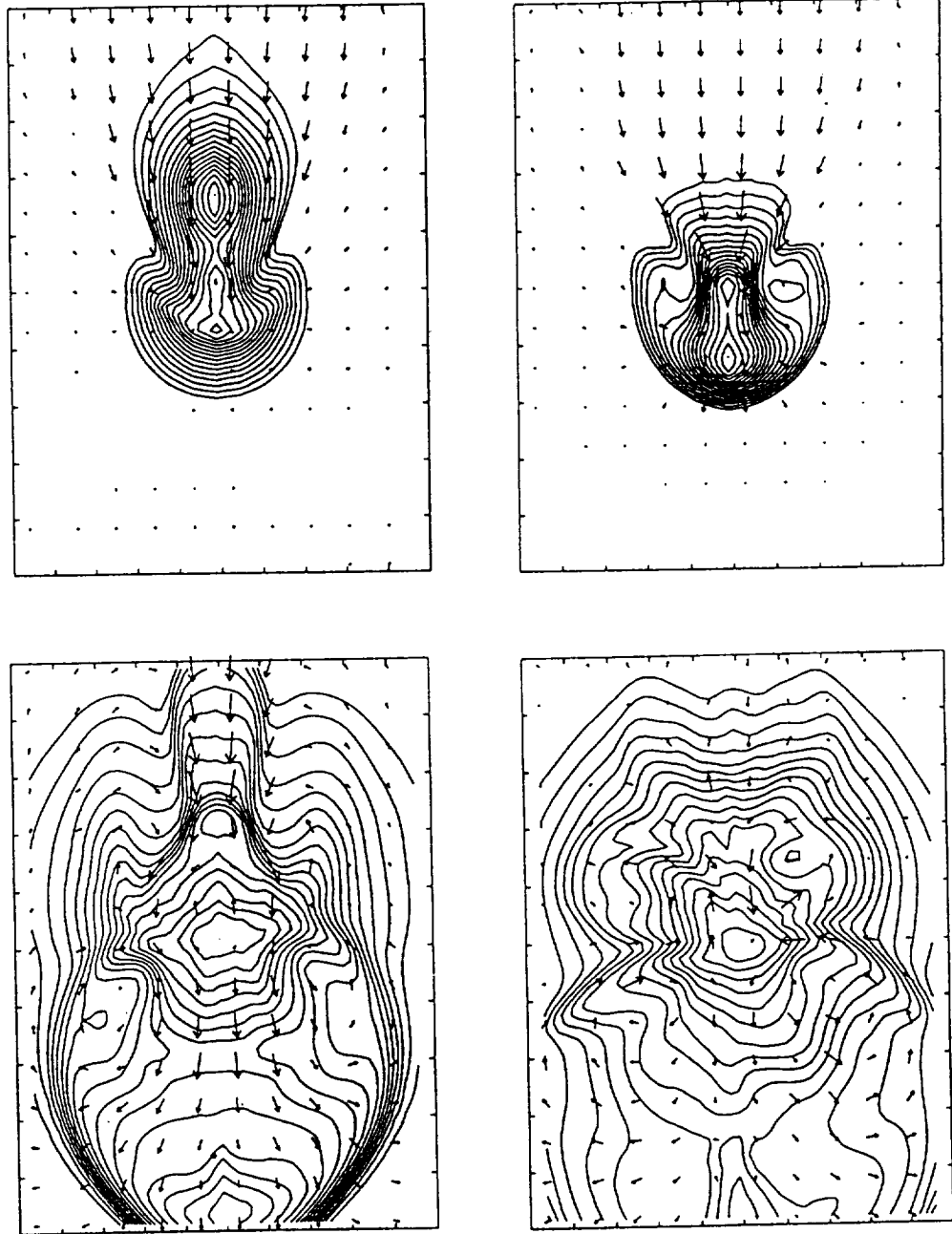


Fig. 3. Synthetic x-ray surface brightness images resulting from a numerical N-body/hydro simulation of 2 merging clusters. The poor cluster, merging from the top, is initially 12.5% the mass, 50% of the core radius, and 25% the temperature of the rich, central cluster.

may be responsible for producing and bending extended radio plasma in radio galaxies; the radio plasma strongly reflects the local gas dynamics and may thus serve as the only currently available probe of ICM gas motions. Our overall impression from extensive examinations of radio and x-ray images is that clusters with radio galaxies are still dynamically evolving at the present epoch.

ACKNOWLEDGEMENTS

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